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ARMSTRONG LABORATORY

CONSTRUCTION OF A DUAL AXIS FORCE REFLECTION STICK AND TEST STATION

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This technical report has been reviewed and is approved for publication.

Peter A. Lurker

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13. ABSTRACT *(Maximum 200 words)*

This report describes the construction of a dual axis force reflecting stick controller and test station which was constructed through the use of basic research funds (ILIR monies). The prototype described in this report is powered only by electric motors and used the latest technology in computers. This was an advancement over a previous prototype which involved pneumatic devices and was very large, bulky, and awkward to use. An experiment was conducted with 5 subjects as described herein to test the overall system for its use in experimental design. The motivation for developing such a small test station for the use of force reflection in stick controllers is because with this new compact and portable system, many new applications now appear for this technology. The system described herein minimizes both weight and electric power requirements to produce the same force reflection. By upgrading the technology in the components used in this test station, wider use of force reflection is now available for a host of new applications.

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PREFACE

The experiments described in this report were made possible by the Armstrong Laboratory under workunit ILIRBB09. Inclusive dates of research were performed from Oct 89 - Sep 91. The Project Manager for this workunit is Dr Dan W. Repperger, AL/CFBS. The authors of this technical report would like to thank Sgt Mike Swisher for his early work in developing previous prototypes of the device described in this report. The support of Steve Bolia of Systems Research Laboratory is gratefully acknowledged for directing the machining of the physical device and coordinating its work to completion. Finally the efforts of Vanessa Deer and Laura Sexton in the typing and preparatin of this report were valuable for the completion of this effort.

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INTRODUCTION

This report describes the construction of a dual axes force reflecting stick controller and test station. The development of this device was accomplished during 1990-1991 through the support of Laboratory Director Funds (LDF); and presently it resides in Building 33, Armstrong Laboratory Wright-Patterson Air Force Base, Ohio. A former prototype involving the concept of a force reflecting stick (in only one axis) was previously constructed using pneumatic actuators. The earlier prototype proved to be unusable in special situations due to its large weight and the requirement that it must have a nitrogen gas source to power the force reflection characteristics that were desired. Therefore the purpose of this effort is to expand the use of force reflecting stick controllers to other situations and uses.

The goal of the utilization of these LDF monies was to construct a 2 axes stick controller that would reflect forces in both axes (pitch and roll), but the force reflection must be driven only by small electric torque motors. The entire unit must be reasonably compact, operate only via electricity, and the motors must provide adequate force reflection. Such a device will be used in studies with the Dynamic Environment Simulator (DES) centrifuge to investigate how force reflection can prevent pilots from having undesirable biodynamic responses as they interact with the complex acceleration fields. A second use for this device occurs in studies with VA patients who suffer from arm spasticity. This arm spasticity is usually a consequence of head injury, spinal cord injury, or other military related accidents. A large portion of patients at VA centers cannot presently operate wheelchairs due to their spastic arm motions which makes the control of a moving wheelchair a potentially dangerous situation. If, however, these patients were given force reflecting stick controllers, their muscle spasms, thus allowing them to more safely operate devices like wheelchairs. In short, the purpose of the LDF effort was to simplify, to make more compact, and to allow for force reflecting test stations to be more widely used in both the centrifuge experiments and in the reduction of spasticity study involving the VA patients.

FORCE REFLECTION

The interest in using force reflecting stick controllers initially came as a result of data analyzed in a displacement stick experiment on the DES centrifuge [1] in 1982. In this experiment, it was observed that if a centrifuge subject made a stick response in a lateral or side-to-side direction, and if, simultaneously, an external acceleration field (lateral $\pm$ Gy) was produced in a direction to <u>oppose</u> the original hand motion, then tracking performance improved. The improvement in tracking performance was a consequence of the subject's hand response appearing to be smoother due to the force reflection. This force reflection was naturally induced via the centrifuge motion. The experiment described in [1] led to the concept that, perhaps, in a static (1 Gz) environment, if force reflection was used to

emulate the complex G field in the centrifuge study [1], that, tracking performance may again improve.

Tests were then conducted in a ground based (1 Gz) simulator in which a pneumatic force reflecting stick was built. This large device required an external nitrogen gas source to power the one pneumatic actuator used to provide the force reflection in only the lateral axis. The collection of data and the control of the force reflecting stick required a mainframe computer (PDP-11). This was a bulky and awkward procedure to use such a device, but it served its purpose through the collection of valuable empirical data on force reflection.

The interesting result from the static stick study was that the same type of tracking performance improvement was observed to occur [2] when the force reflecting algorithm was constructed at 1 Gz to reproduce the identical effect as was discovered in the centrifuge experiment under complex acceleration conditions. Studies in force reflection were then conducted in a variety of different areas. For example [3], it was shown that the transfer functions characterizing the relationship between stick output to both hand position input and hand force input to the stick changed dramatically when force reflection was used. This led to the investigation of how human muscle function [4] may change as a consequence of the use of these devices. The human is known to inherently be a very adaptable system. Thus these results were not surprising. Finally a variety of different force reflection strategies were investigated [5-6] to see how the force reflection regime could be better coordinated with the task at hand, the properties of the human arm, and other variables that influence the tracking task scenario. These studies have now led to a proposal to the Veterens Administration (VA) [7] for a four year effort to investigate force reflection with spastic VA patients. In this application, force reflection will be used productively to reduce the spastic responses made by the patients as they move displacement type stick controllers. These controllers are typical of those used on wheelchairs to manipulate these vehicles through commonly occurring driving scenarios encountered.

EARLY PNEUMATIC FORCE REFLECTING STICK CONTROLLERS

Figure 1 illustrates the early pneumatic device. Figure 2 diagrams the electromechanical and pneumatic parts that describe its operation. In figure 2, the manner that force reflection is accomplished can be described as follows: the displacement stick is connected via a gear coupled to a rack and pinion which is connected to a piston inside the airtight cylinder. The piston has area A and two different pressures P1 and P2 exist on each side of the piston. If $P1 > P2$, then a force [$F= A(P1-P2)$] is produced on the connecting shaft which transmits a force F to the rack and pinion. The net torque acting on the stick is the force F multiplied by the radius of the gear attached to the displacement stick. The counter torque exerted by the human subject back on the stick is his force (where he holds the stick) multiplied by the distance this force is located from the point of the

pivot. The key to the operation of this device and the principle of force reflection is based on how the pressures P1 and P2 change within the cylinder. To produce these pressures, two electric current-to-pressure transducers in the diagram change the pressures P1 and P2 through the changes in the electrical currents I1 and I2, respectively. The "smart algorithm" from the computer box refers to analog circuit signals (from the PDP-11 mainframe computer) which generate the currents I1 and I2 based on desired force reflection algorithms. The engineer must design the appropriate force reflection algorithms to produce the electrical currents I1 and I2 which, in turn, produce the appropriate force reflection responses during the dynamic operation of this device.

DISADVANTAGES OF THE PNEUMATIC STICK CONTROLLER

The disadvantages of the pneumatic device to produce force reflection are obvious. The excessive weight, the requirement to have a nitrogen gas source, and also a mainframe computer (PDP-11) were required to operate the current to pressure transducers for force reflection. It is much more desirable to have a more compact, lightweight, less complex system. These simplifications will also improve the reliability of such a device.

Another obvious disadvantage of the pneumatic device occurs in the operation of the electric current/pressure transducers. Figure (3) (Ref 2) illustrates plots of the electric current input and net force output of the two devices illustrated in figure 2. The first obvious difference observed in figure 3 is that the characteristics of the two transducers differ from one another both in slope and the threshold points where force first is produced. To compensate for these differences, special electrical circuits had to be built to initially start at different bias points and also to produce the same slope for both transducers. Figures 4 and 5 illustrate how these circuits were designed for the base current and voltage circuit. One obvious disadvantage of the current transducers is hysteresis. With reference to figure 3, when going up a current-force curve and returning down the curve, the same path is not always traversed. Also there are limits of maximum force output from both curves. Obviously in the design of the circuits in figure 4, the valve V1 had the minimum force output, and the valve V2 had to be operated in a limited portion of its range to match up with the weaker valve, V1. Thus, the weakest valve limits the overall capability of this pneumatic system.

For these many reasons it seemed appropriate to use new technology in this area. This includes rare earth magnet motors (torque motors) which have high torque/weight ratio. There is also a need to remove the cumberson nitrogen gas source. The DC motor technology also allows more linear operation over a wider dynamic range which makes it more appealing. Thus the thrust of this LDF effort was to develop an electrically actuated 2 axes system to

replace the 1 axis pneumatic system. It was hoped that the performance of the new electrical system would match or surpass the performance of the pneumatic system.

DESIGN OF LIMITED ANGLE TORQUERS FOR FORCE REFLECTION

As a first step in providing force reflection using only electrical actuators, two torque motors were purchased [Inland model QT-3802-B (8)]. These motors operate differently from the pneumatic system previously described. Figure (6) illustrates the operation of a DC motor to account for both the torque output produced and the induced voltage relationship that exists across its terminals.

When a voltage, Vin, is initially impressed across the motor, a large electric current, Ia, flows due to the limited resistance of the internal windings of the armature of the motor. The value of this large initial current (Ia) is typically 10 times the steady state current in such a motor. The equations governing the operation of a DC motor are as follows:

Voltage Equation: $$Vin = Ia\ Ra + ein \tag{1}$$

Induced Voltage Equation: $$ein = Km\ \phi\ W \tag{2}$$

Torque Equation: $$Tau_m = Km\ \phi\ Ia \tag{3}$$

In the voltage equation (1), Ra refers to the internal resistance of the windings, Ia is the armature current, and ein is the induced voltage which appears across the armature terminals. In equation (2), Km refers to the induced voltage motor constant, O is the external field (which is a constant and obtained from the DC permanent magnets) and W is the angular velocity of the shaft.

Thus:

$$ein = K_m'\ W \tag{4}$$

is a simplification that can be used [where K_m' represents the product of Km and ϕ in equation (2)]. In the torque equation (3), Tau_m refers to the torque output at the shaft. This is matched by the load demands. In the absence of the load, with little friction, the inertia J of the shaft is accelerated via:

$$Tau_m = J\ (d/dt)\ W \tag{5}$$

Thus the shaft gradually accelerates at a rate proportional to the torque applied. This, of course, is assuming the friction terms are reasonably small.

What makes the DC motor operate differently from the pneumatic device is in the initial high value of current Ia which rushes in when the motor is first turned on, or is suddenly reversed. This is typical of operation of limited angle torquers with human subjects in which many quick reversals of direction are constantly occurring. Also, typically, a DC motor is used for continuous

operation. This means the shaft turns continuously. For this application involving torque motors, however, human subjects will only all ~ part of a revolution of the motor to occur. Since motors are not normally designed for this type of operation, other problems may occur due to the overheating of the windings, excessive wear on a limited portion of the path between the external field (stator) and the rotor, and other consequences associated with this unusual use of a DC motor.

The limiting of the initial current Ia and the reversal of the motor (due to human commands) at arbitrary points in time can be handled via the power electronics which control its operation.

POWER ELECTRONICS

The overall force reflecting stick test bench station is shown in figure (7). The main power system (9) involves a 28 v dc, 14 amp supply source. From this source a $\pm$ 15 v dc (.5 amp input) supply is required to provide the -15 volts bias to the servo amps. The potentiometers also need $\pm$ 15 volts to the x and y position displacements and for the analog feedback circuitry.

The servo amplifiers used in the power electronics are Inland model EM19-28080-A00 amplifiers. They were used as a linear DC servo amplifier configured as a current gain device. The stated gain of the amplifier is 3.5 amps/volt. Internal current limiting circuitry is included in the design, and for this application is limited to 4 amps of the total 7 amps that could be supplied. To provide the reflective force to the subjects, the expression:

$$Icl = 2/ Rcl \tag{6}$$

where Icl refers to the input current into the torque motors [Inland model QT-3802-B] and Rcl is the effective resistance seen by the current source. As described previously the input current limits the actual torque output provided by these motors through the torque constant.

The motor construction consisted of three basic parts:

(1) A stator was constructed using rare earth magnets (Samarium Colbalt), (2) A wire wound rotor with 20 poles was used, and (3) A brush assembly was included.

These torque motors are designed to operate in a stalled condition for long periods of time and have a peak torque rating of 4.8 ft-lb. The torque sensitivity Kt is listed as 0.6 lb ft/amp. Included on both axes of the stick is a dc tachometer (Inland model TG-1318-C). This device converts mechanical rotation into a DC output voltage and the polarity of the output is dependent on the direction of rotation. The rated voltage sensitivity Kg of the tachometer is 0.18 v dc/(rad/s). Also on each axis of the force stick is a 50K ohm rotational potentiometer to provide position information to the computer generating the tracking task. The feedback shaper block consists of a low pass filter, a

circuit to adjust the gain of the feedback, and a circuit to allow for a threshold adjustment. At this time all of these circuits are breadboarded and easily reconfigured for experimentation. Future testing will incorporate a microcomputer to handle the feedback algorithms in software and is described in the sequel.

In figure 7 the purpose of the feedback shaper is to reduce noise from both the pots and the tachs when these signals are measured. The microcomputer in figure 7 is a 386 Tandy - 4000 which receives the tach and pot signals in both the roll and pitch axes. Within this computer, the gains in both the position and rate feedback loops can be changed and when summed, the output signal to the torque motors (in both axes) can be made any function of the input signals. Thus simple PID (position, integral, derivative) feedback is possible as well as any nonlinear algorithm that may be required. Advanced prototypes of this device will replace the computer by a chip device with a specific force reflection algorithm burned in the chip hardware.

An exploded drawing of the motor/tachometer/potentiometer housing is shown in figure 8. This housing is constructed completely of aluminum. Figure 9 illustrates the actual stick swivel assembly, and how the motor housing is attached. The direct coupling of the motor to the axle eliminates any reduction in developed torque due to a gear train. This is termed a "direct drive system" in both pitch and roll axes.

IMPLEMENTATION USING A MICROCOMPUTER

After the hardware described in the last section was built and tested, it became obvious that it would be much simpler to change the gains of the feedback for force reflection and run the tracking task using a microcomputer. To assist in this project, a National Instruments PC-Lab board was purchased to be used with a 386- Tandy 4000 computer. The National Instruments Board has measurements for 4 distinct analogs reads and can output two analog signals to the power electronics. A program was written in Microsoft Quick C to run both the tracking task, the force reflection algorithms, for data collection, and also for performance scoring. Figure (10) illustrates the overall system. The user can now simply input the desired force reflection algorithms (position and/or rate gains in both the roll and pitch axes of the stick). Also a tracking task scenario was developed for the VA study previously described. This scenario can easily be changed in software as to the frequency and amplitude of the target. In addition, another performance task was developed which incorporates force reflection and Fitts' Law. This special performance task involves properties of human reaction time but also determines the human operator's information capacity with metrics involving information theory.

A Pilot Study To Evaluate The Overall System

To illustrate the robustness of the system to extensive testing,

an experimental paradigm was developed to test the system. Five subjects were run with a set of experimental conditions as described in figure 11. Subjects had four force reflection conditions: passive stick (no force reflection), Kp=1 (a pure spring gain), Kv=1 (a pure dashpot), and the fourth condition (Kp=.5 and Kv=.5) which is a complex mechanical impedance. The tracking task developed was a Fitts' law paradigm (Ref 10) as displayed in figure 12. The subjects had to move the cursor of size c to be within the box of width w in minimum time. Three values of w and three values of c were selected and subjects tracked three replications of four force reflection algorithms times three different values of w multiplied by three values of c for a total of 36x3= 108 trials a day. This procedure was followed for four days. The data collected on the fourth day were used in the final analysis and these data are discussed in the next section. The important issue of Fitts' law is the ratio of the amplitude of movement A to three tolerance [tolerance is defined as = (w-c)] values used in this experiment. Since three w values and three c values were selected, for this choice of box and cursor sizes, there existed a total of 6 distinctly different tolerances. Table I illustrates the actual physical measurements and tolerance values. It is noted that a geometric relationship is implicit in this experimental design whereas A divided by any tolerance value is an integer. All integers are geometrically related to a basis number or least common denominator (lcd). This provides a wide range of variable values that can be used to thoroughly investigate the impact of force reflection on Fitts' law as discussed in the next section.

Table I - Definitions and Parameter Values

Let A = 15" = 120/8"
w1= 1", w2= 1.25", w3= 1.75"
c1 = .25", c2= .50", c3 = .75"
Tolerance = Tol(i,j) = wi - cj

Tol(1,1) = 3/8,	Tol(1,2) = 2/8,	Tol(1,3) = 1/8
Tol(2,1) = 4/8,	Tol(2,2) = 3/8,	Tol(2,3) = 2/8
Tol(3,1) = 6/8,	Tol(3,2) = 5/8,	Tol(3,3) = 4/8

Note: 120 is twice the lowest common numerator of all tolerances, i.e. 120 = 1x2x2x3x5*2

Empirical Data From The Pilot Study

Figure 13 illustrates a Fitts' law diagram of the data obtained when averaged over the five subjects in this force reflection experiment. To account for the between subject variability and to see the rank ordering of the force reflection conditions, the reaction times are expressed as a percent of the 4.32 bits of difficulty task (and then averaged across subjects). The 4.32 bit task was selected because it is midrange in difficulty and least subject to experimental artifact. Figure 14 shows a typical subject with the actual reaction times displayed. From the

results of this preliminary study, one can see for tasks of this nature (defined as target tasks), the impact of force reflection has no apparent advantage across subjects. The reaction time increase with difficulty is linear in the range 3.32 bits to 4.91 bits. Possibly the 5.91 bit difficult task is extremely difficult and requires different motor response as compared to the other tasks. Thus using the 5.91 bit task is outside the data base of the other tasks and it biases the results of the other tasks.

The results of force reflection not showing benefits for target like tasks has also been found in previous studies. It demonstrates the fact that in specific applications, the apparent advantage of force reflection is not immediately seen. It is in the regulation task (a task where the force and task enter at the same point - at the stick controller) where the advantage of force reflection occurs. Figure 15 illustrates the difference between the target and the regulation type task as it appears to the human operator. The target task requires cognitive processing based on direct visual signals with the human output = the hand response. In the regulation task, however, the disturbance is closer to the sensory feedback channel (force reflection) and thus can be more easily affected by the proper force reflection algorithm. Another way to view this effect is that in the regulation task, the force loop is not only faster but also it is closer to the spinal reflex type of behavior as contrasted to the target task. The stimulus response time for visual stimulus, hand response (target tracking) is 160 msec. On the other hand the stimulus input (force at hand) to hand response is as low as 70 msec. This shortened response time coupled with the fact that by applying the force at the hand when the disturbance is at this point in the loop, provides a faster loop and an enhanced tracking scenario for the human operator. The next study will examine the difference between the target task considered here and the regulation task, in which previous studies have shown the significant impact of force reflection on performance.

SUMMARY AND CONCLUSIONS

A dual axes force reflection stick controller was developed using only electrical actuators. This apparatus is highly portable and easy to operate. It is also completely controlled via a microcomputer. A pilot study revealed that force reflection algorithms with this device show similar results from those used with the former pneumatic system which was bulky and awkward to use. A target task was used to validate the present electrically actuated device. The results obtained so far concur with human performance determined previously involving studies involving pneumatic actuators. Force reflection technology offers great promise in the area of manual control and as a transitioning technology, has application in the control of wheelchairs, heavy equipment, and high performance aircraft.

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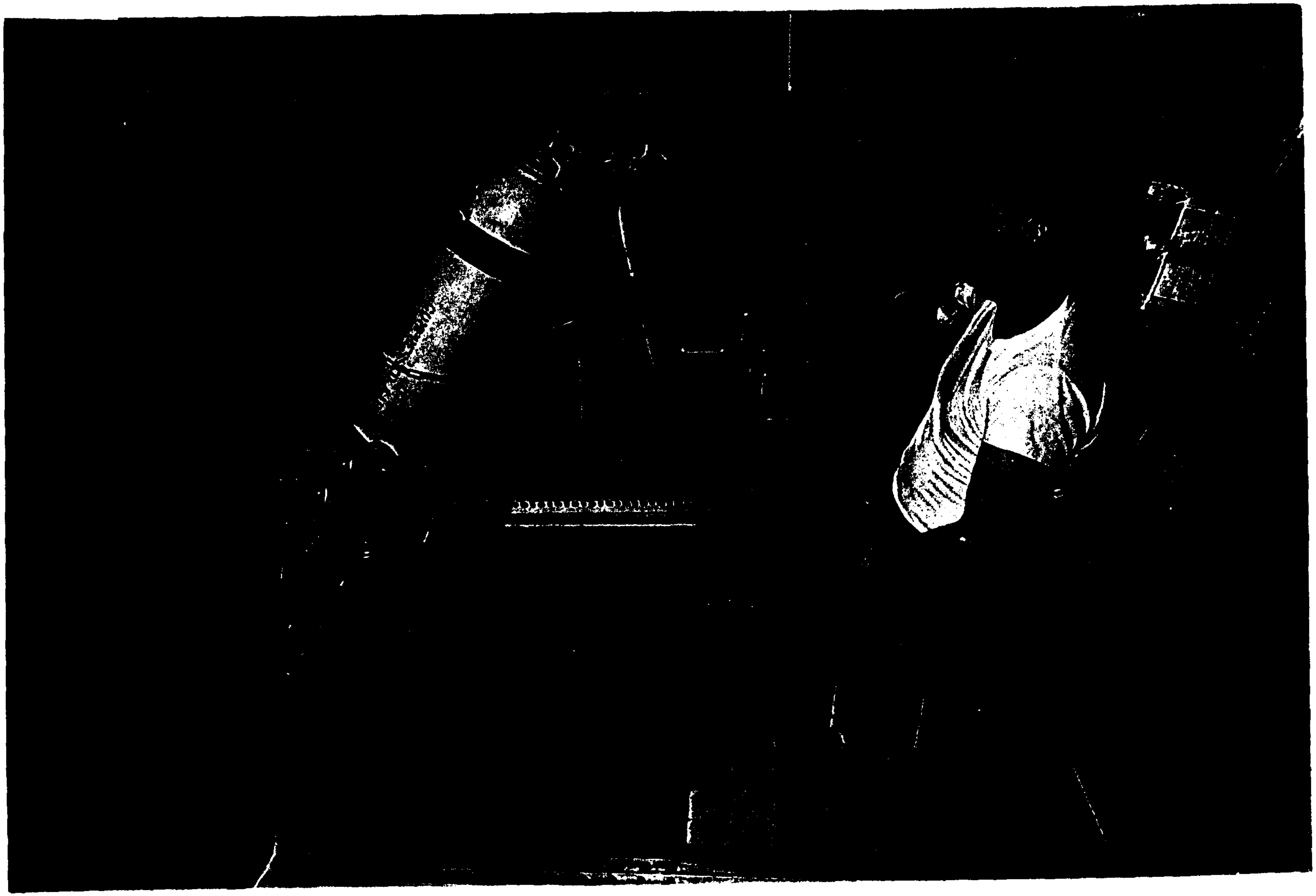
Figure (1) - The Early Pneumatic Device



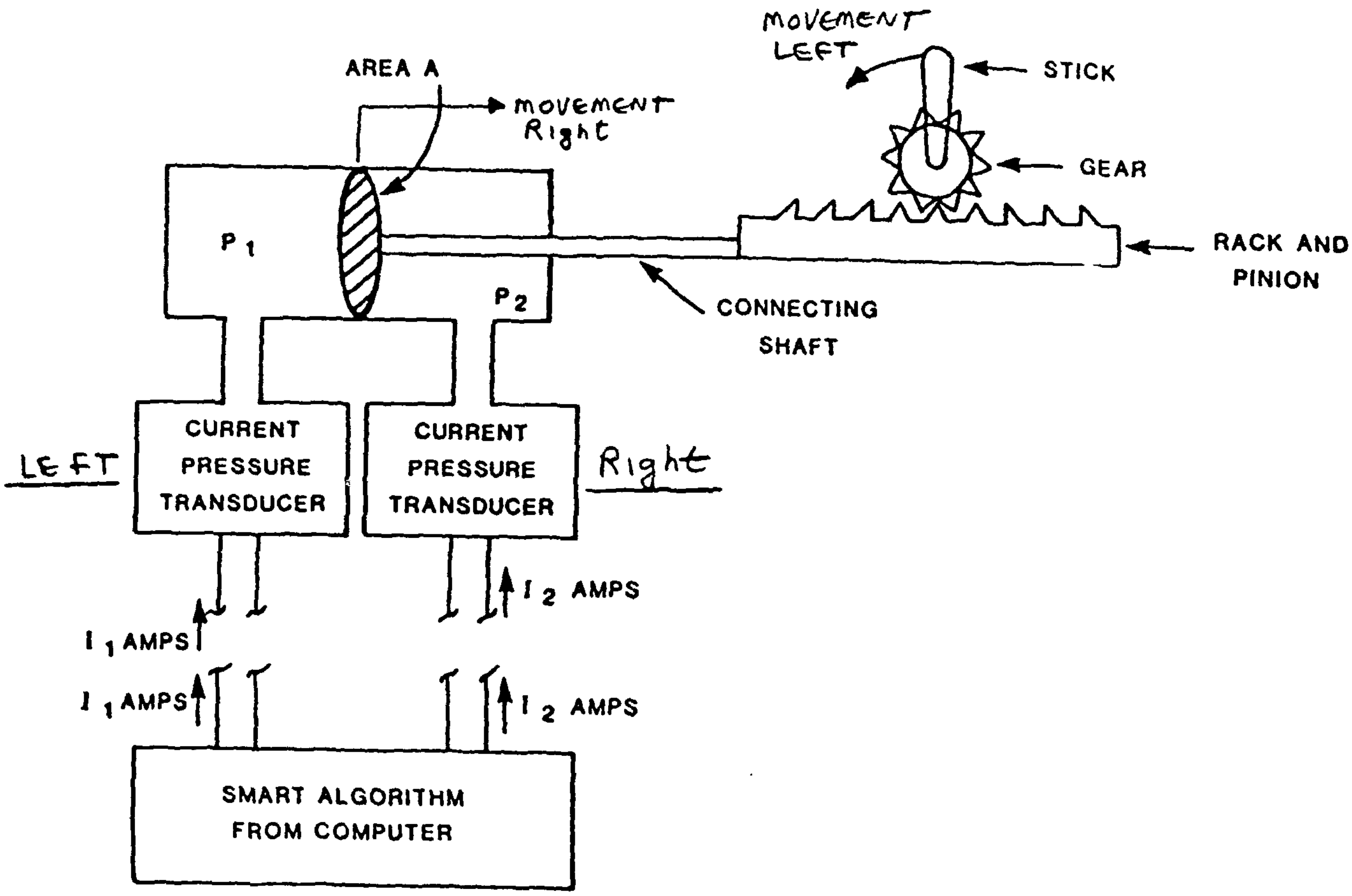


Figure (2) - The Electro-Mechanical System

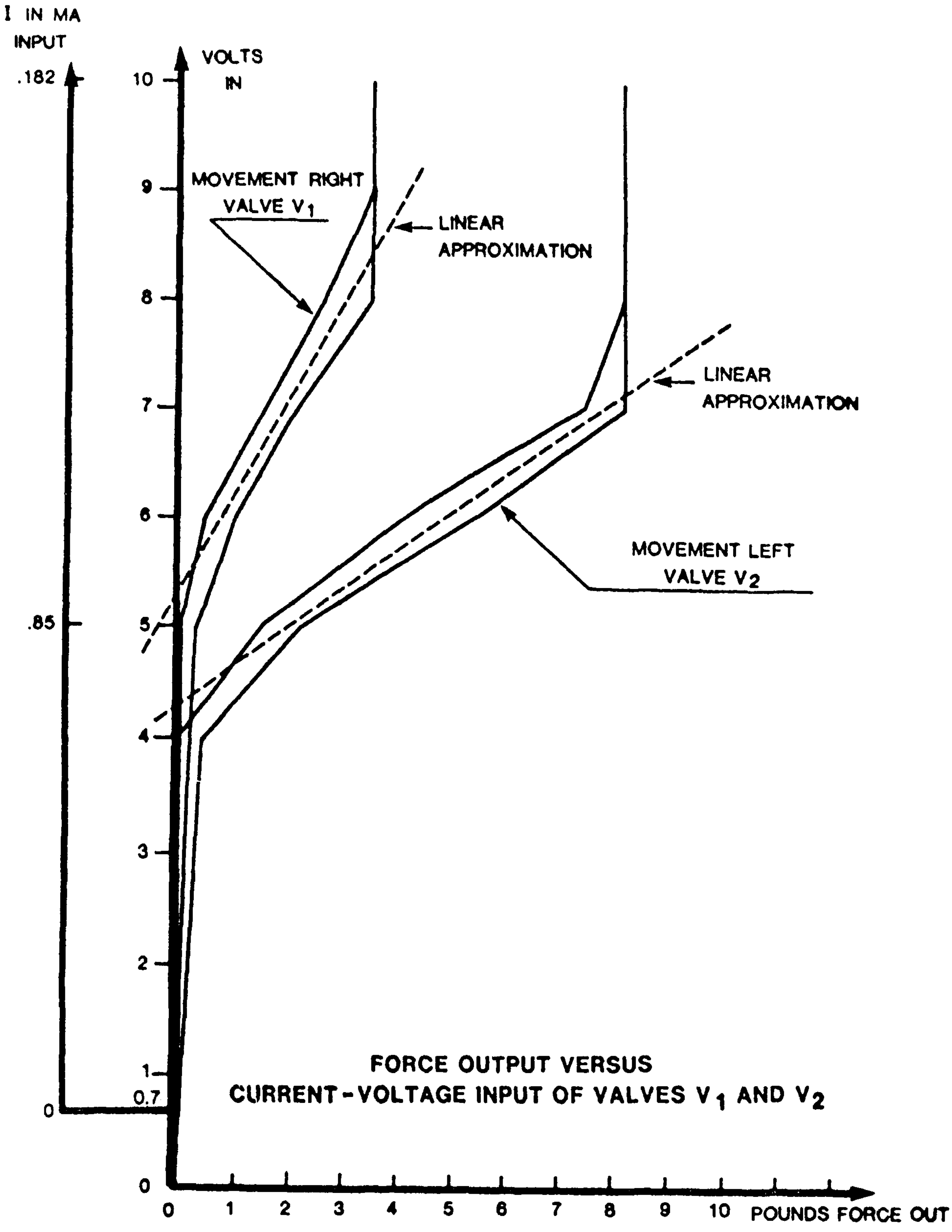


Figure (3) - Different Valve Characteristics

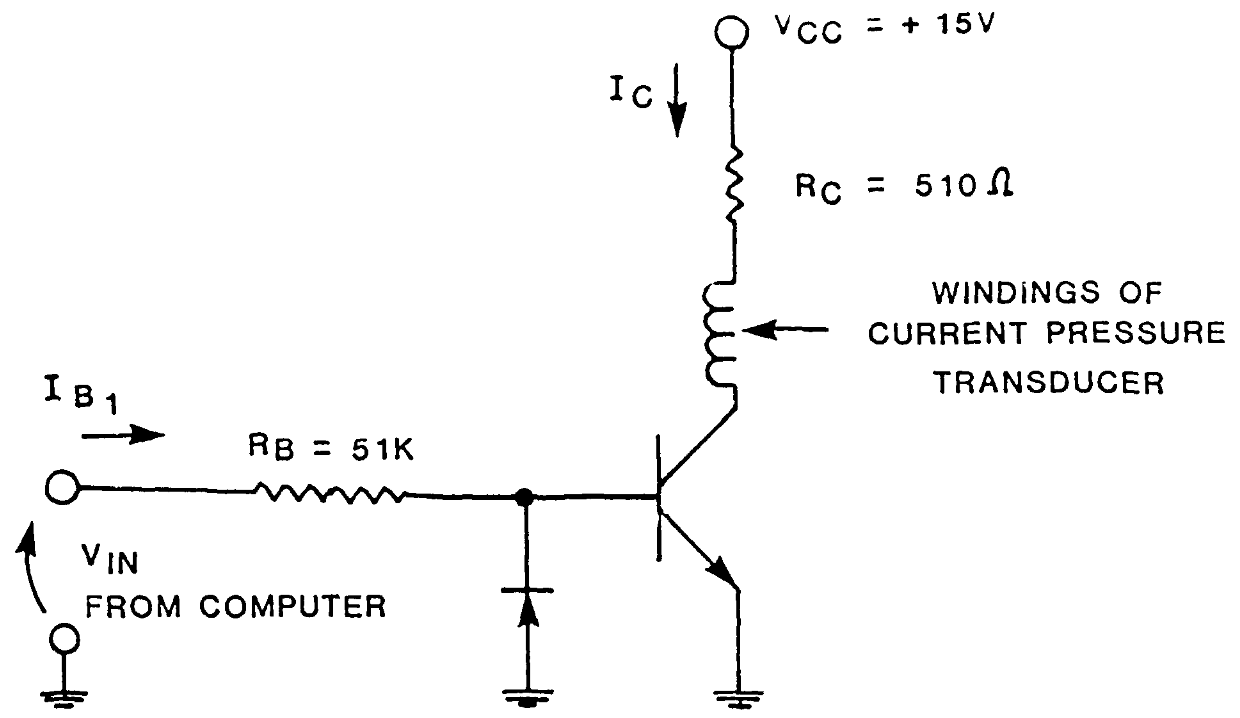


Figure 4 - THE CURRENT LIMITED ELECTRICAL CIRCUIT TO DRIVE THE CURRENT-FORCE TRANSDUCER

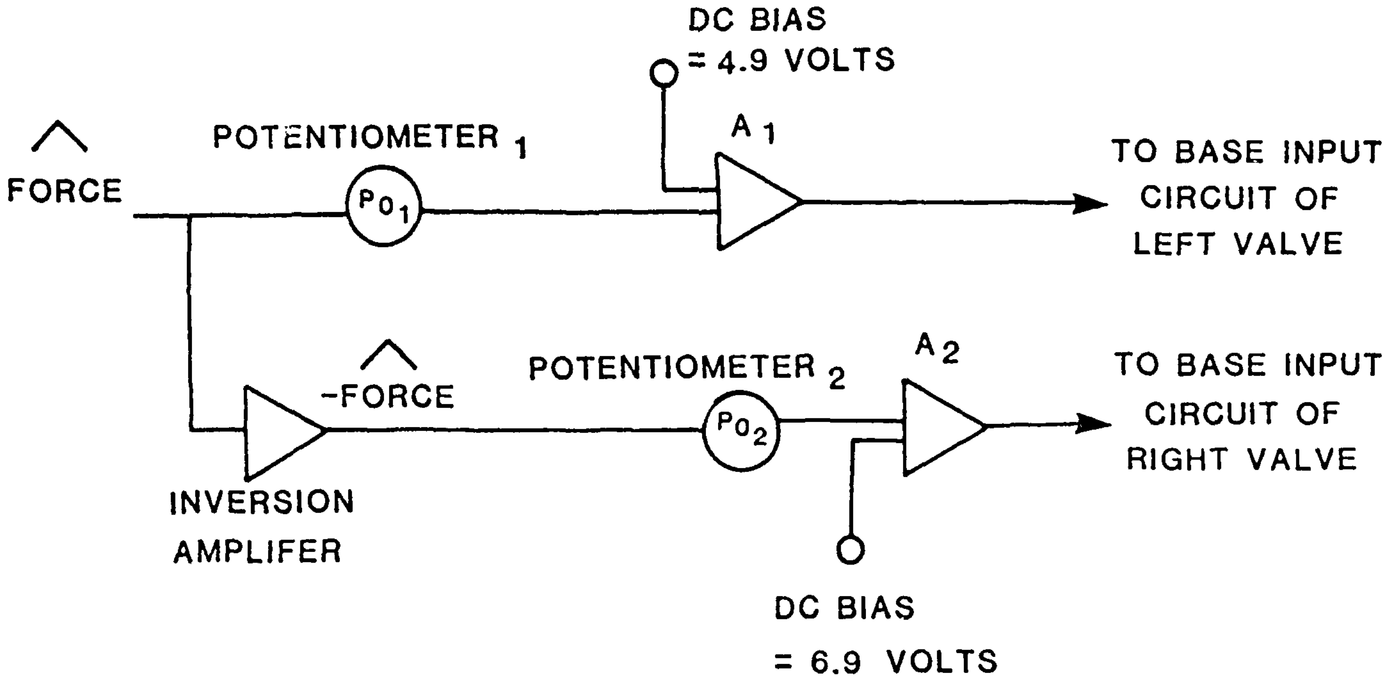


Figure 5 - THE ANALOG COMPUTER DIAGRAM

A DC MOTOR (CONSTANT FIELD EXCITATION)

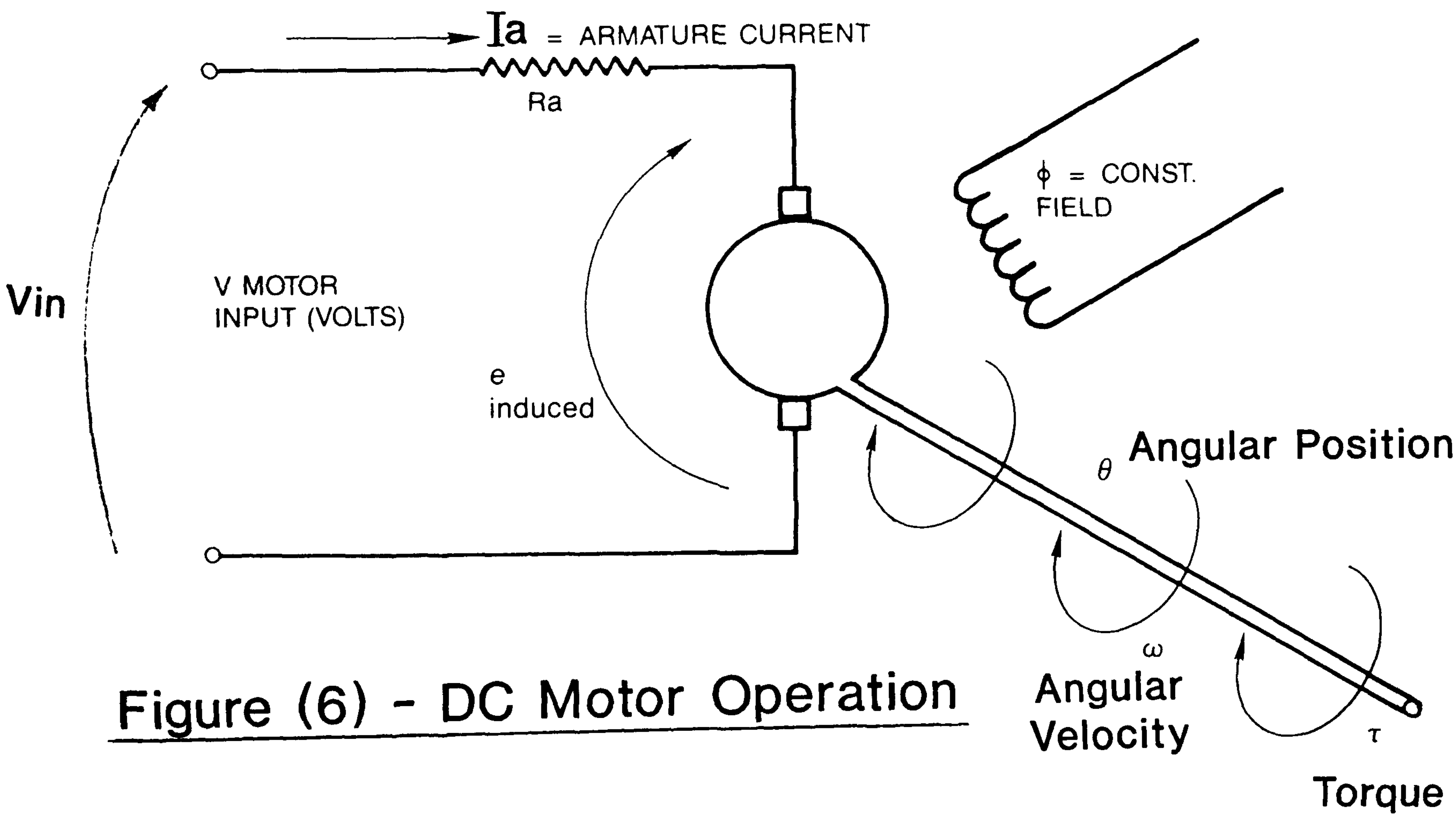


Figure (6) - DC Motor Operation

FIGURE (7)

FEEDBACK SHAPERS BUILT IN HARDWARE

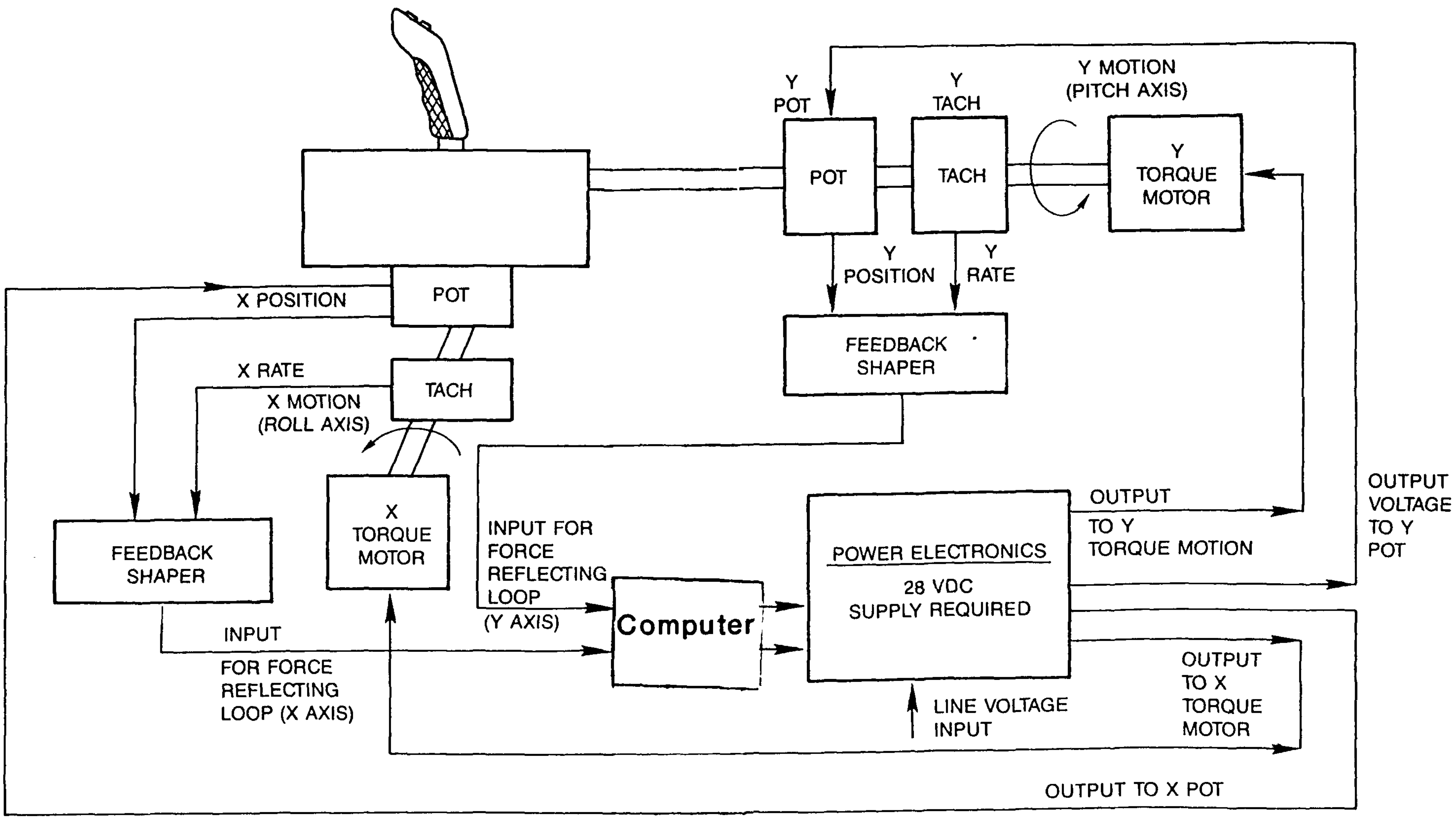
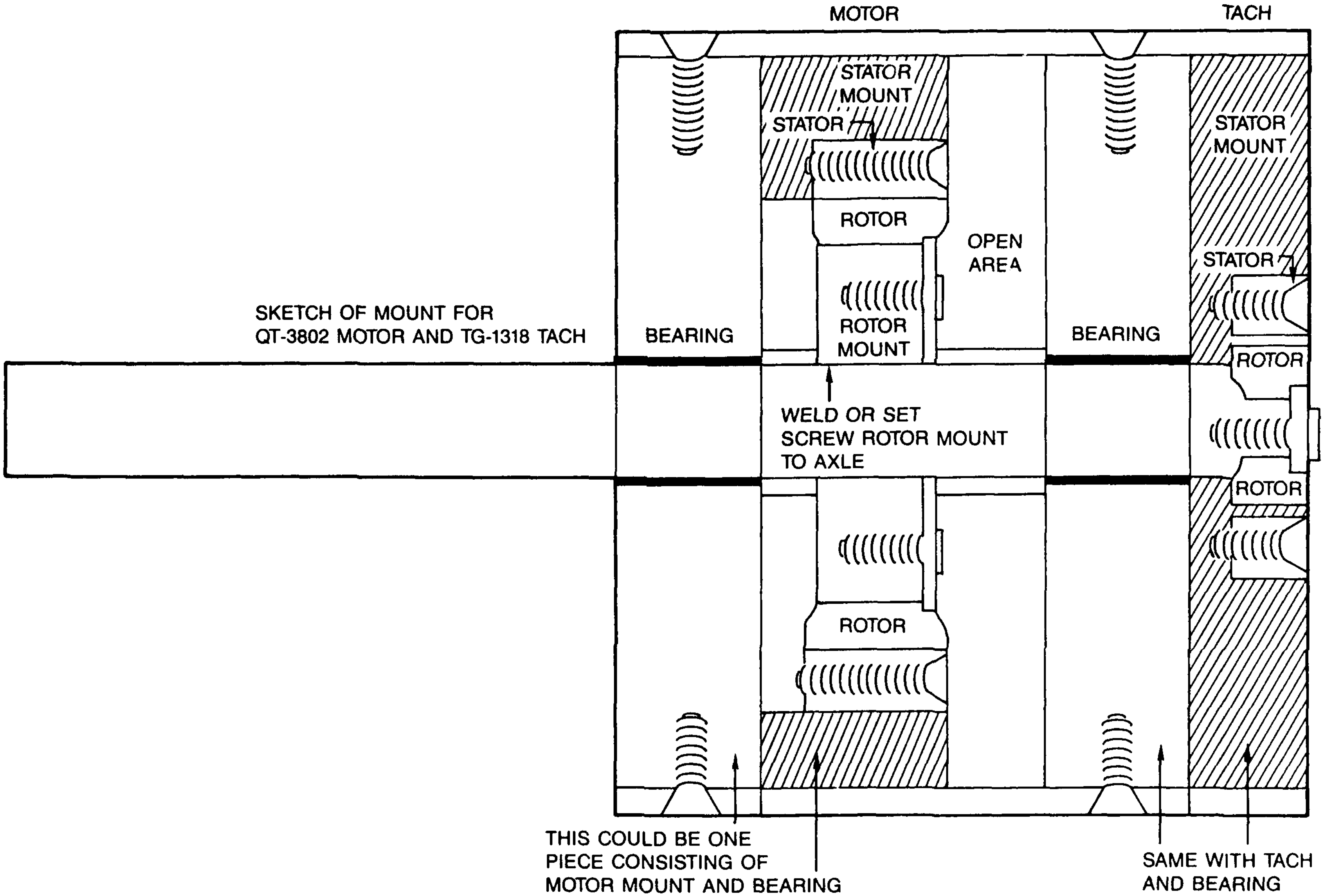


FIGURE (8)

NON MAG STAINLESS



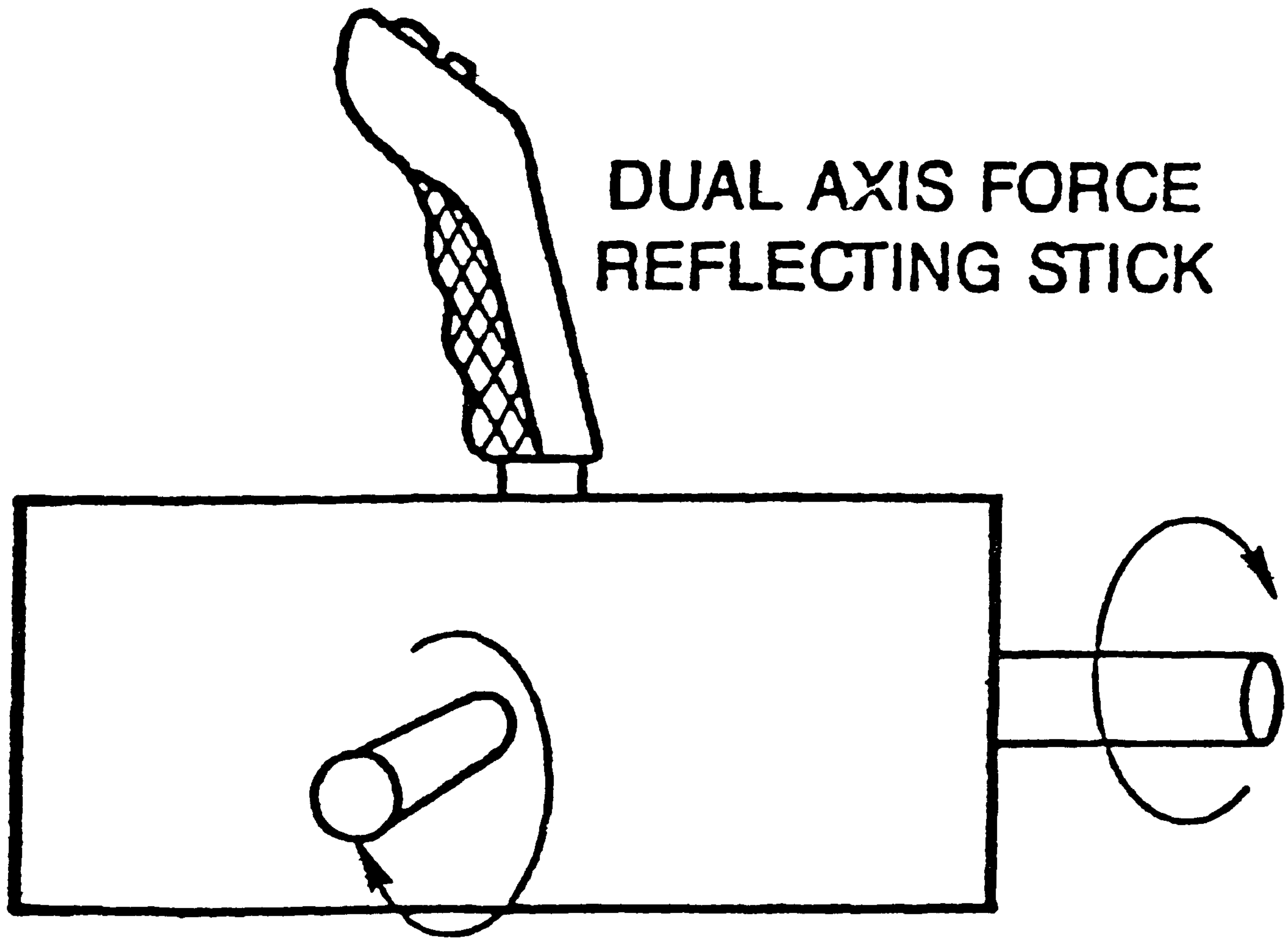
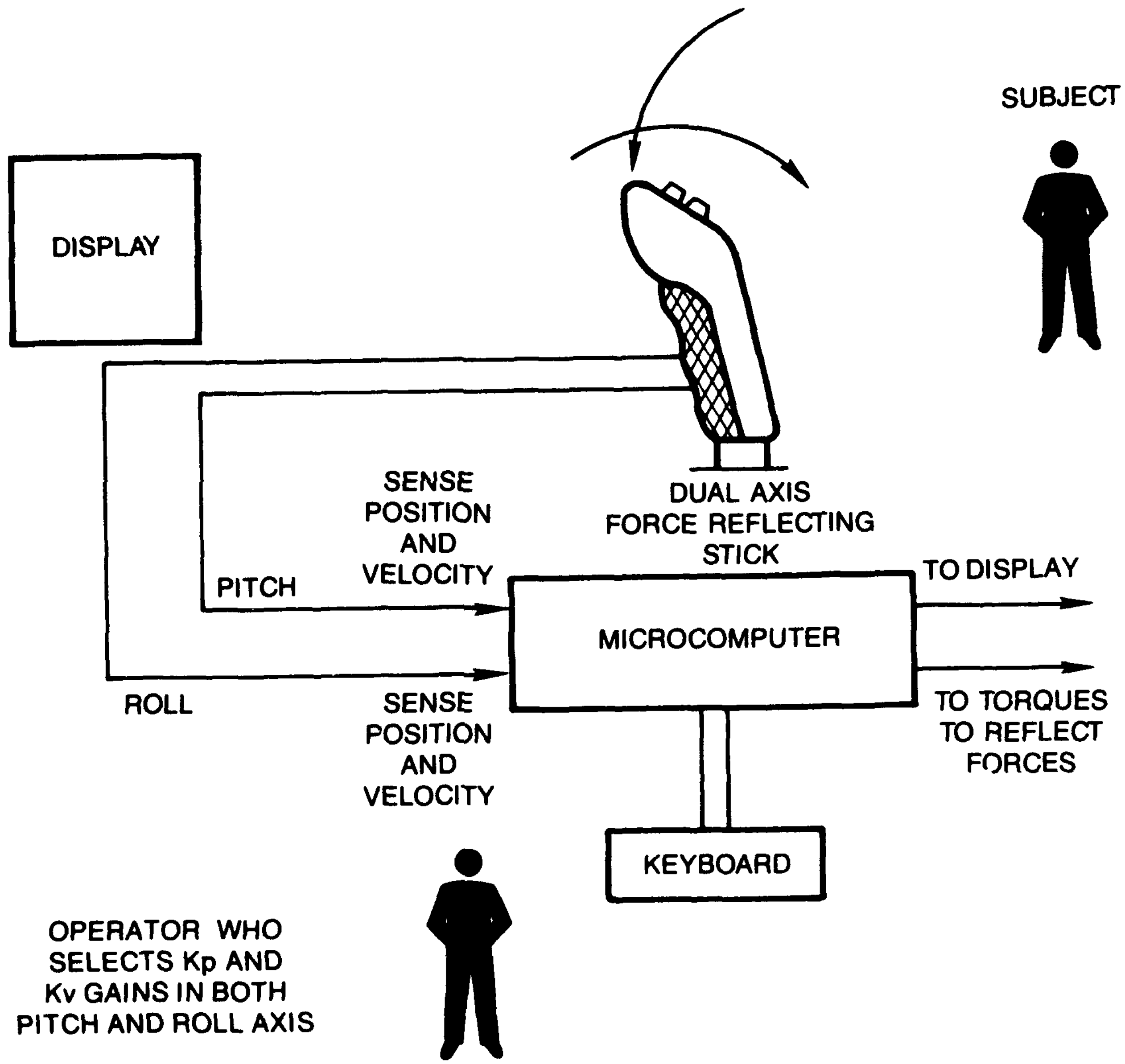


Figure (9) - The Actual Stick Swivel Assembly

(FIGURE 10)

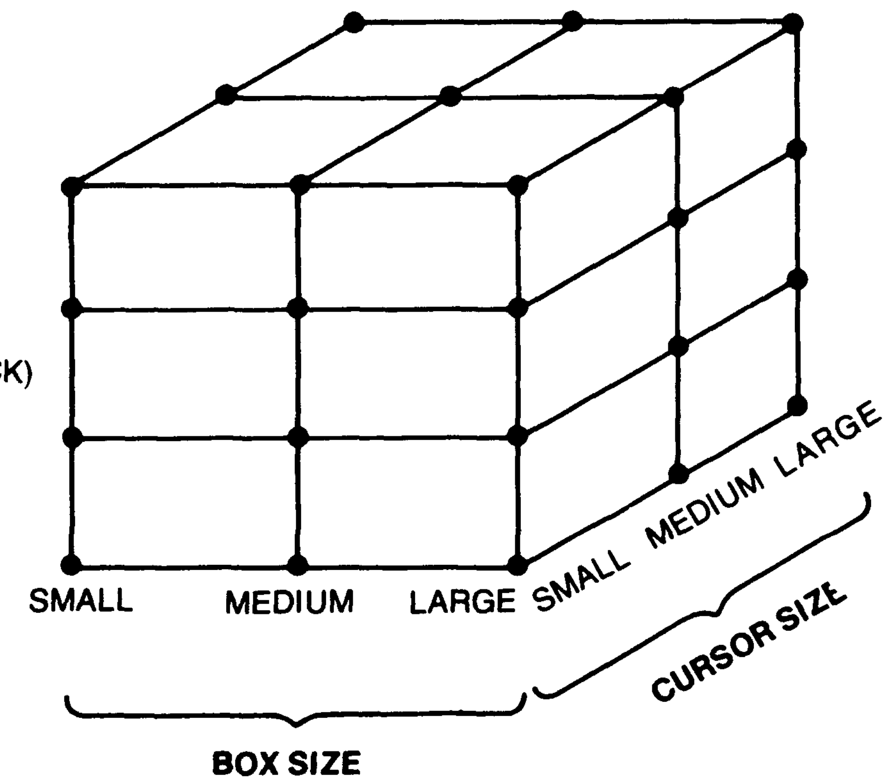
THE OVERALL SYSTEM



(FIGURE 11)

EXPERIMENTAL DESIGN CONDITIONS

ONE-THIRD OF ONE DATA DAY



Kp = Kv = 0
(PASSIVE STICK)

Kp = 0.5, Kv = 0.5
(MIXED MECHANICAL IMPEDANCE STICK)

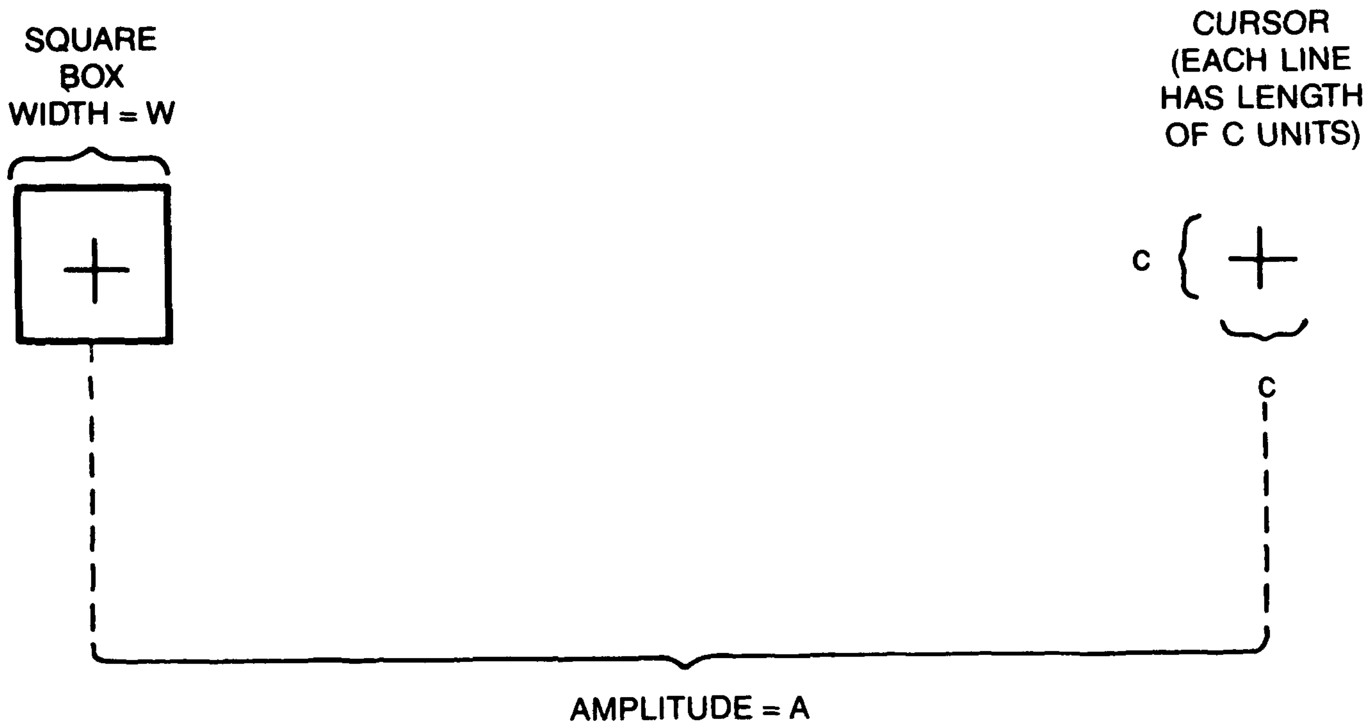
Kp = 0, Kv = 1
(PURE DASHPOT STICK)

Kp = 1, Kv = 0
(STRONG SPRING STICK)

ALL 36 CONDITIONS (4 × 3 × 3)
ARE REPEATED 3 TIMES EACH
DATA DAY FOR A TOTAL OF
4 DATA DAYS

(FIGURE 12)

THE FITTS' LAW PARADIGM



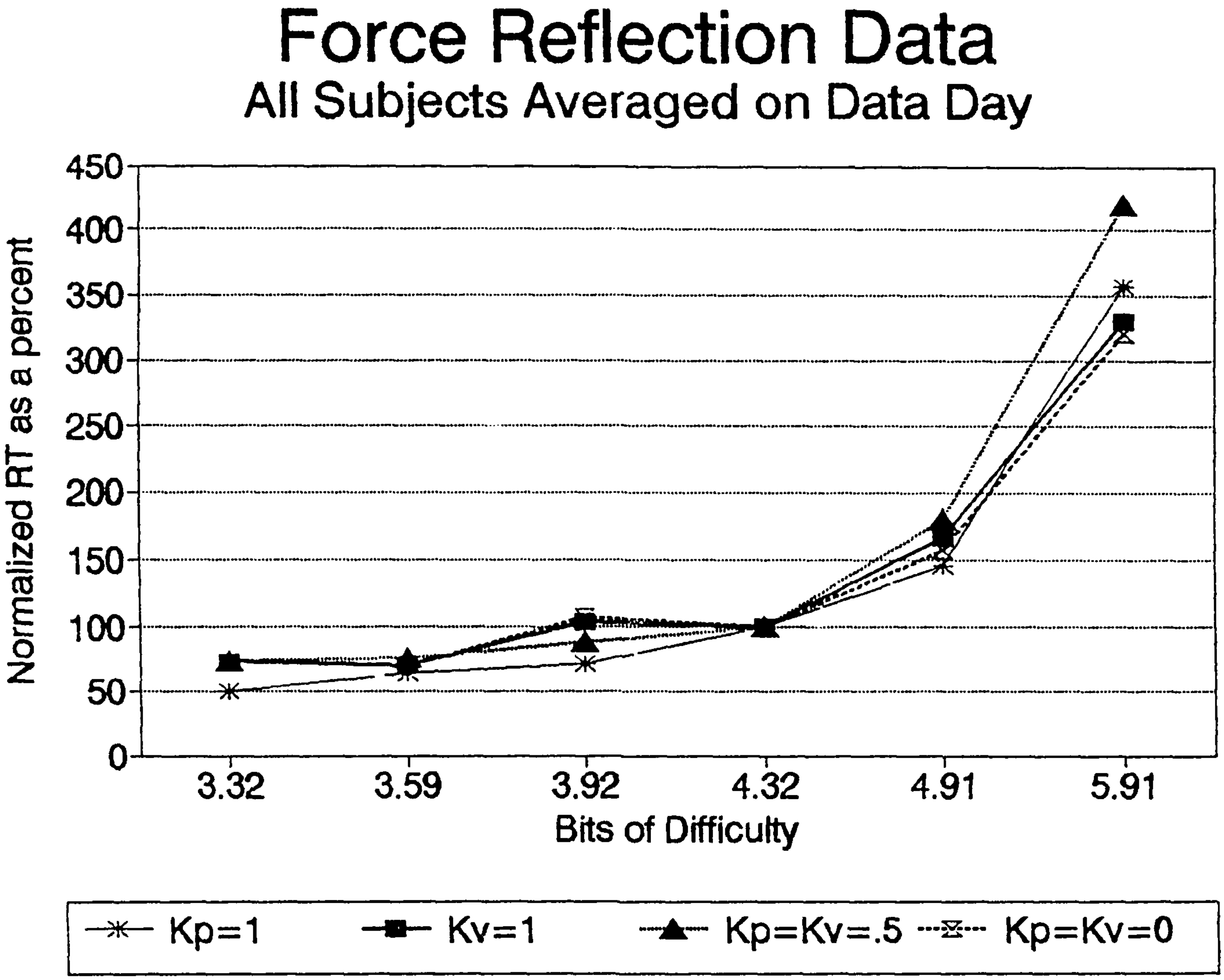


Figure (13) - Data Averaged Across All Subjects on The Final Day

Force Reflection Data

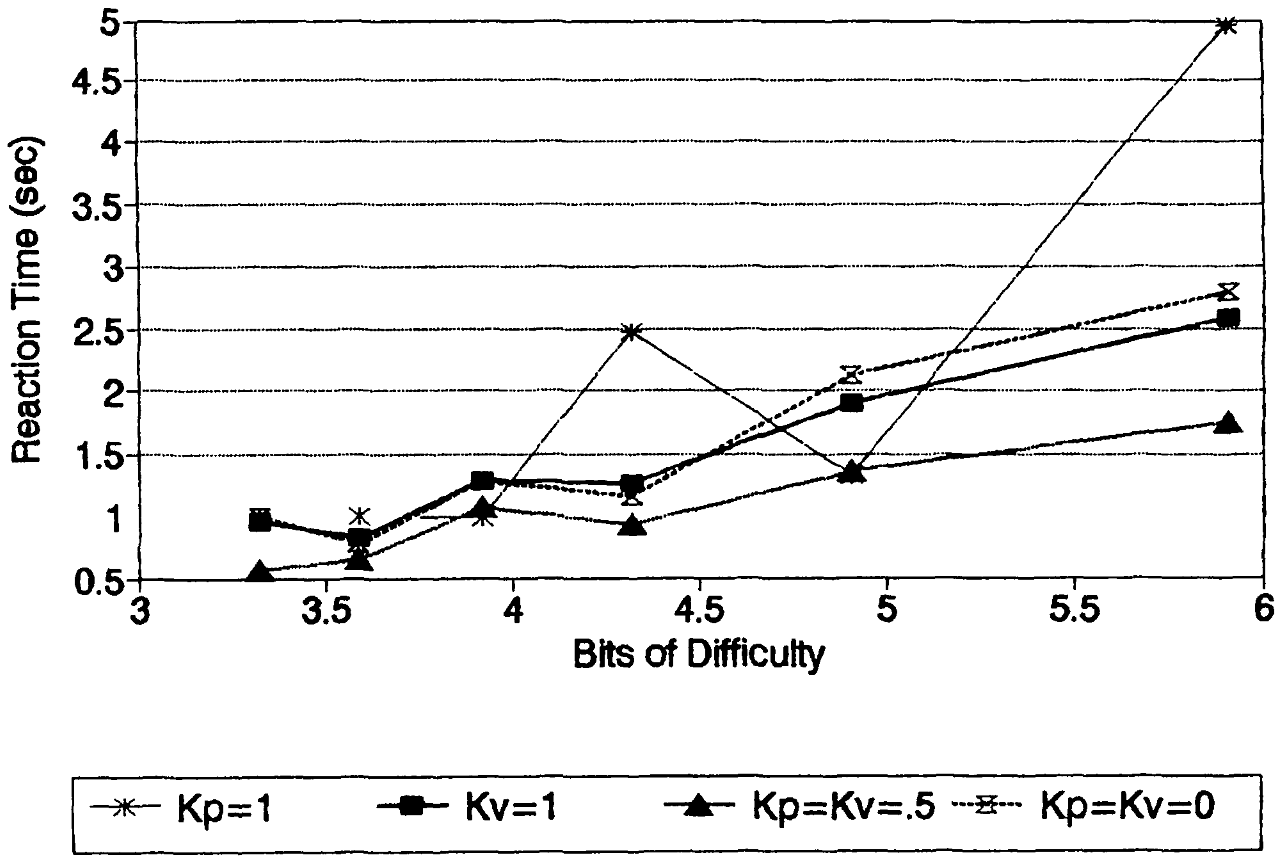
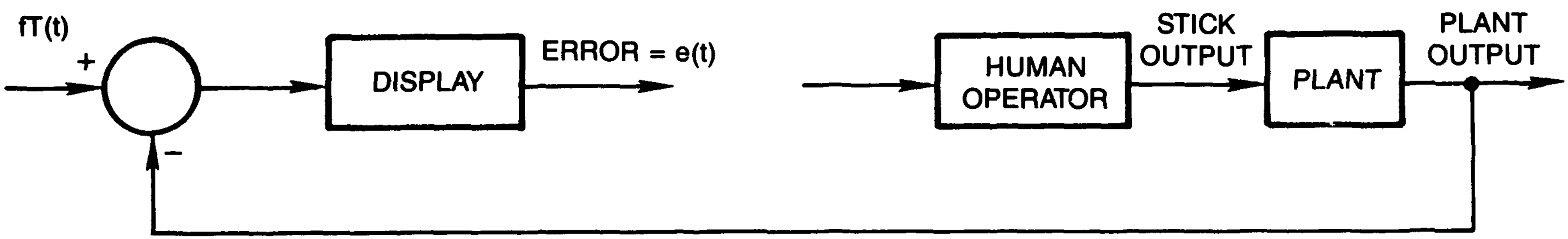


Figure (14) - One Subject on The Final Data Day

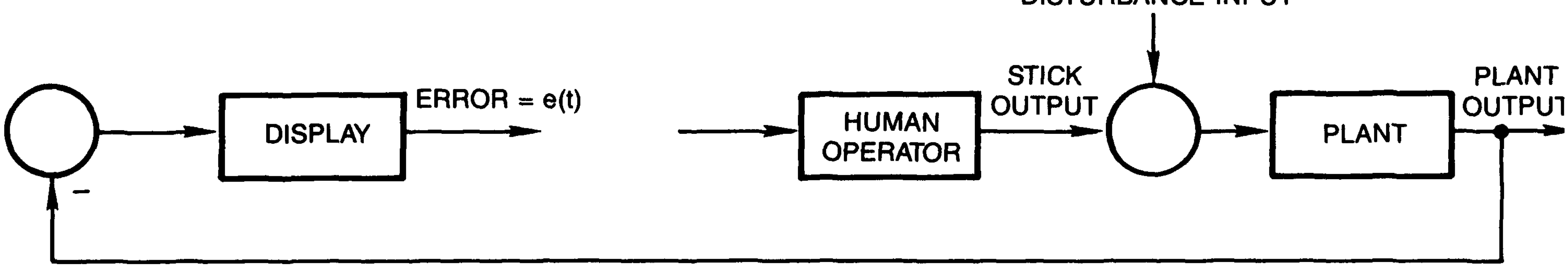
(FIGURE 15)

THE TARGET INPUT TASK VERSUS THE DISTURBANCE INPUT (REGULATION) TASK

THE TARGET INPUT TASK



THE DISTURBANCE INPUT TASK



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